PROGRESS REPORT
November 1, 2002

Assessing Seismic Hazard in Puerto Rico and the Virgin Islands Using the Historical Earthquake Record and Mixed-Mode GPS Geodesy: Collaborative Research Between the University of Puerto Rico, Mayagüez and the University of Texas at El Paso

Grant award number: 01HQGR0041

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Element I
Key Words: GPS continuous, GPS campaign

SUMMARY

This project report is submitted in keeping with the requirements as described in the award. The original grant was awarded to the University of Puerto Rico, Mayagüez, but subsequently was transferred to the University of Arkansas due to the relocation of the PI's from Puerto Rico to Arkansas. A start date of January 1, 2001 and a completion date of December 31, 2002 were assigned to the project at the University of Arkansas.

Data to assess seismic hazard in Puerto Rico and the Virgin Islands were obtained using Global Positioning System (GPS) geodesy. Measurements were collected at 21 campaign and 6 continuous sites. Emphasis is on quantifying surface displacement of active faults. Preliminary results derived from data from a subset of the existing GPS network are consistent with deformation on the island of Puerto Rico limited to less than a few mm/yr, including areas where active faults are proposed. Most of the active faulting occurs offshore north of the island of Puerto Rico, where displacements of 16 mm/yr must be accommodated. More recent results are consistent with westward increasing EW-oriented extension from the Virgin Islands across Puerto Rico and into eastern Hispaniola. East-west extension of ~3 mm/yr is observed across the island of Puerto Rico, consistent with composite focal mechanisms and regional epicentral distributions. Although the loci of extension are not known, similarity of GPS-derived velocities among sites in eastern Puerto Rico suggest the active structures lie west of the San Juan metropolitan area. Reactivation of the Great Northern and Southern Puerto Rico fault zones as oblique normal faults with right-lateral slip is a possibility. East-west extension of ~2 mm/yr also must exist between eastern Puerto Rico and Virgin Gorda. These extensional belts allow eastward transfer of slip between North America and the Caribbean from the southern part of the plate boundary zone in the west to the northern segment in the east.

INVESTIGATIONS UNDERTAKEN

Overview and background: Puerto Rico and the Virgin Islands (PRVI) have a long historical record (~400 years) of damaging earthquakes, including the 1916, 1918, and 1943 Mona Passage earthquakes (Ms=7.2, 7.3, and 7.5 respectively), the 1867 Anegada Passage earthquake (Ms=7.3), the 1787 Puerto Rico trench earthquake (M=7.5?) and the 1670 San German earthquake (M=6.5?)[(1)]. Current seismicity mimics the pattern of the large, historic events.

Earthquakes are concentrated offshore Puerto Rico in the Mona and Anegada Passages, the Muertos Trough, and the Puerto Rico trench. The highest levels of onshore seismicity are in southwest Puerto Rico in the Lajas Valley, an EW-trending feature, which continues west offshore and passes south of the southern termination of the Mona Canyon (Figures 1 and 2).

During the last two decades, significant progress has been made toward assessing the seismic hazard of PRVI. This includes the establishment and continued enhancement of the Puerto Rico Seismic Network, the development of regional tectonic models, the recognition of microplate behavior in the northeastern Caribbean, the documentation of potentially active faults onshore and offshore, and the assessment of relative motion between the Caribbean and North America plates. Despite advances in the state of knowledge, however, key aspects of the fundamental geologic and geophysical underpinnings necessary to delineate seismic source zones for evaluation of seismic risk remain either largely unconstrained or controversial. These are summarized in three points.

- *What is the nature of deformation in the plate boundary zone near PRVI, i.e. does the zone contain distinct rigid blocks which move separately from one another or are displacements taken up continuously across its width in simple shear?*
- *Where are the active faults?*
- *What is the mechanical behavior of mapped and potentially active faults, i.e. are the faults locked and accumulating strain that must be released catastrophically during a significant earthquake or are the faults creeping aseismically?*

These questions must be answered to evaluate seismic risk quantitatively and to plan appropriately for development of civil infrastructure. The only published earthquake hazard map for Puerto Rico[2] for example, does not include calculation of the risk of rupture of specific faults because reliable data on deformation rates across seismogenic structures were not available. A 1999 draft USGS hazard map, which used the sparse GPS-velocity field in (3) to partition slip among various areal zones roughly coincident with mapped onshore and offshore features, yields probability for damaging ground motion in western Puerto Rico equivalent to that for Seattle, Washington.

Better definition of the possible seismogenic features within the northeastern Caribbean and their potential associated slip is essential to assessing earthquake hazard and establishing appropriate actions to mitigate seismic risk. One of the most powerful techniques to provide such data is Global Positioning System (GPS) geodesy, which can obtain positions of points on Earth's surface to a precision of a few millimeters. Changes in positions over time allow scientists to pinpoint locations of active faults, document their associated displacement and mechanical behavior, and model the deformation field to improve understanding of the potential for destructive earthquakes. GPS arrays now are an integral part of earthquake monitoring networks worldwide.

This project emphasizes the collection and analysis of surface deformation data obtained from mixed-mode Global Positioning System (GPS) geodetic studies, on-going in PRVI since 1994, to determine slip rates and strain accumulation along active structures in PRVI. The project is part of a collaborative study with the University of Texas at El Paso (UTEP) of historic earthquakes of M>6.0 occurring from 1906 to 1960 to identify possible seismogenic structures and to estimate how much of the deformation has been released seismically over the past 80 to 90 years. The existing PRVI mixed-mode GPS array consists of 4 continuous GPS sites and 21 campaign sites. Three continuous sites and 11 campaign sites were added as part of our USGS-NEHRP work. During the upcoming year, we plan to install two more continuous GPS sites (St.

Thomas and the eastern Dominican Republic) and an as yet undetermined number of campaign GPS sites, depending upon our preliminary results. In addition, 2 continuous GPS sites exist within the region (PUR3 and CRO1), which we do not maintain but for which we process data.

Tectonic setting: Puerto Rico and the Virgin Islands are located within the broad EW-trending boundary between the Caribbean and North American plates in the northeastern corner of the Caribbean (Figure 1). The boundary is characterized primarily by left-lateral motion along predominantly east-west striking faults. The eastern half of the boundary in Hispaniola, Puerto Rico and the Virgin Islands is a complex deformation zone ~250 km wide, whose northern and southern limits are defined by the Puerto Rico trench and the Muertos trough, respectively. Three proposed microplates lie within this diffuse boundary zone (Figure 1). From west to east, there are (1) the Gonave(4), (2) the Hispaniola(5) and (3) the Puerto Rico-northern Virgin Islands (PRVI)(6). Such a microplate model assumes that nearly all of the deformation associated with North America-Caribbean motion is concentrated along the faults that bound the three rigid blocks: the Oriente, Septentrional, Enriquillo-Plantain Garden, and Anegada faults, the Muertos trough and North Hispaniola deformed belt, and the Mona rift faults northwest of Puerto Rico (Figure 1).

Global Positioning System (GPS) geodetic data from CANAPE (CAribbean-North American Plate Experiment) constrain motion of the Caribbean plate at Cabo Rojo in the southernmost Dominican Republic relative to North America as 20.6±1.2 mm/yr toward N89°E±3°(3). Recent GPS-derived velocities relative to North America from the interior of the Caribbean plate at San Andres Island (12.524°N, 81.729°W) in the west and Aves Island (15.667°N, 63.618°W) in the east may be modeled with error, along with the Cabo Rojo velocity, using a single pole of rotation(7), supporting the assumption that the southern Dominican Republic is part of the rigid Caribbean plate.

On-land faulting: Prevailing scientific opinion is that PRVI remains rigid and that deformation occurs primarily on the bounding structures of the microplate. The question arises as to how rigid is "rigid PRVI"? Do faults exist within PRVI, particularly onshore, that are capable of producing significant and locally damaging earthquakes? The highest levels of onshore seismicity are in the southwest corner of Puerto Rico in the Lajas Valley(8). Less than 20 km north of the Lajas Valley, recent research has identified the surficial expressions of the Cordillera and Joyuda faults, which may be correlated with a WNW/ESE trend across southwestern Puerto Rico that is defined by a series of epicenters of small earthquakes that were recorded by the Puerto Rico Seismic Network in 1995(9).

In addition, the island of Puerto Rico is traversed by two northwest-southeast striking fault zones: 1) the Great Northern Puerto Rico fault zone (GNPRFZ) and 2) the Great Southern Puerto Rico fault zone (GSPRFZ). The fault zones were active during the Eocene and record predominantly thrust and left-lateral displacement(10). Field evidence for post-Oligocene motion along the fault is sparse, supporting a rigid PRVI since the Miocene. Both the GNPRFZ and the southern end of the GSPRFZ are covered by little deformed Neogene strata. The two fault zones, however, represent large areas of weakness within PRVI along which intrablock motion may be localized. Indeed, the southern end of the GSPRFZ immediately offshore may cut and disturb Recent shelf sediments (11, 12). The projection of the northern end of the GSPRFZ, which continues offshore into Mona Canyon, is sub-parallel, however, to faults of similar orientation (NW/SE), which are seismically active (11, 13). An EW-striking splay of the GSPRFZ, the Cerro Goden fault, cuts across to the west coast of Puerto Rico about 10 km north of the city of Mayagüez. Whether Quaternary motion occurred along the Cerro-Goden fault is unknown, although the offshore projection merges with other mapped structures that presumably are Quaternary in age. Recent displacement with components of normal motion and left-lateral strike-slip has been inferred on the basis of offset stream drainages and terraces [14].

GPS data collection: Although the grant was not awarded until April 2000 in Puerto Rico and January 2001 in Arkansas, we report on data gathered since October 1999. During the 2000 calender year and subsequently in the 2001 and 2002 calender years, data were collected at 21 campaign sites in Puerto Rico and the Virgin Islands in addition to the three previously existing continuous sites (GEOL on the roof of the Physics building at UPRM and operated by us; PUR3 in western Puerto Rico and maintained by NOAA; and CRO1 in St. Croix and run by IGS). A continuous site was installed in Fajardo (FAJA) early in 1999, another was established in San Juan (UPRR) in October 2000 and yet another in Humacao (UPRH) in November 2000. Of the 21 campaign sites occupied in 2000, 2001, and 2002 nine were added to the network after the 1999 campaigns.

GPS campaign data were obtained with Trimble 4000 SSi 12-channel, dual-frequency, code phase receivers equipped with Trimble Dorn-Margolin type choke ring antennae. Data were collected and archived at a 30 s epoch using a 10° elevation mask. A minimum of 8 hours of GPS data per UTC observation day was collected during all campaign occupations. The majority of sites had more data as a result of 16-24 hours of observations during each UTC day. The University of Puerto Rico, Mayagüez (UPRM) (GEOL, FAJA, UPRH, and UPRR), National Oceanographic and Atmospheric Administration (NOAA) (PUR3), and IGS (CRO1) continuous stations all have choke ring antennae and record at 30 s rate to 5° elevation. GEOL, FAJA, UPRR, UPRH, and PUR3 use Trimble 4000SSi receivers. The CRO1 site has an AOA Turbo Rogue receiver.

GPS data processing: GPS geodetic data were processed using the GPS inferred positioning system, orbit analysis, and simulation software package (GIPSY/OASIS II) developed, distributed, and supported by the NASA Jet Propulsion Laboratory (JPL) [15]. Analysis was performed at the University of Arkansas, using GIPSY (version 2.5, update 8a) along with various processing scripts. Receiver independent exchange (RINEX) format data were processed with precise orbit and clock products from JPL. A nonfiducial point-positioning strategy was adopted for all station days, following (3). Free-network solutions were transformed into the international terrestrial reference frame (ITRF00). Errors shown for daily site positions are scaled 1σ errors. Velocity estimates use a weighted least squares fit to daily site positions. Uncertainty on derived velocities reflects an estimate of both white and time-correlated noise, using the methodology of Mao et al., 1999[16] and include a fixed value of monument noise (2 mm $yr^{-1/2}$).

RESULTS

Preliminary results are summarized below. Data from only a subset of the sites in the GPS network were used primarily due to the short time-series on many of the stations. We include data from continuous site FAJA and campaign sites ADJN, ARC2, ZSUA and SALN that were not included in previous reports. We emphasize the analysis of GPS-derived velocities within a fixed Caribbean reference frame. For more detailed discussion, the reader is referred to Jansma et al. (2000) and to Jansma and Mattioli (GSA Special Paper, submitted).

To assess whether the island of Puerto Rico and the the Virgin Islands as a whole are each rigid, we examine GPS-derived velocities of sites in Puerto Rico and the Virgin Islands relative to the Caribbbean. We use the angular velocity that describes motion of the Caribbean plate relative to ITRF00 (International Terrestrial Reference Frame 2000) to predict the Caribbean ITRF00 velocity at each of our GPS sites [7]. We then subtract the predicted Caribbean plate velocity at each site from the GPS-derived site velocity and sum the covariance that describes the uncertainties in both. In the following discussion, we separate the island of Puerto Rico from the neighboring Virgin Islands to the east. Our reasoning is that the potential attachment of Virgin Gorda (GORD) to the Caribbean requires small relative motion between the eastern Virgin Islands and eastern Puerto Rico.

GPS-derived velocities relative to the Caribbean for PRVI appear consistent with a linear increase in velocity from near zero at Virgin Gorda (GORD) in the east to ~3 mm/yr toward the west along the west coast of Puerto Rico, implying east-west extension across the island of 3 mm/yr (Figures 2 and 3). An additional 5 mm/yr of east-west extension is accommodated across the Mona rift. Although all PRVI velocities are similar within error, the systematic pattern suggests that the small differences are likely real, but they are close to the limits of detection in the current geodetic data. The new observations support earlier interpretations that PRVI may be attached to the Caribbean plate at GORD on its eastern end [17]. The preliminary results were based on only 2 epochs (1994 and 1999) of data at GORD. The new dataset includes additional epochs at GORD in 2000 and 2001 and spans seven years. The data from FAJA in the northeastern corner of Puerto Rico and from SALN in south-central Puerto Rico also strengthens the conclusion of east-west extension across the island: the GPS-derived velocities of FAJA and SALN relative to the Caribbean are faster than that of GORD, but slower than that of GEOL, PUR3, PARG, ADJN, and ARC2. The magnitude of the velocity of FAJA also is similar to the magnitude of that at ZSUA, ~35 km to the west. The azimuths vary by 45°.

How the extension is accommodated across the island of Puerto Rico is not clear. Extension may be distributed across several small features or localized along a few major structures (e.g. the Great Northern Puerto Rico Fault Zone where the extension would generate dextral transtension). Higher than average levels of seismicity do occur along the central segment of the GNPRFZ [8]. The GPS-derived velocity relative to the Caribbean at ZSUA, a site between PUR3 and FAJA, is identical within error to that at FAJA, suggesting that the structures that take up displacement are located west of the San Juan metropolitan area. We note that several NS-trending valleys that channel the major rivers along the north coast of Puerto Rico exist and may be manifestations of extension. The observation of likely ENE-WSW extension across Puerto Rico is not surprising. Results from previous GPS studies and marine geophysical surveys document east-west extension between western Puerto Rico and eastern Hispaniola [17-20]. The GPS geodetic data suggest that east-west extension is not limited to the offshore regions, but affects the island of Puerto Rico, albeit to a lesser degree. Orientations of T-axes from composite focal mechanisms also indicate east-west extension across eastern Puerto Rico [21].

REPORTS PUBLISHED

Calais, E., Y. Mazabraud, B. Mercier de Lepinay, P. Mann, G. Mattioli and P. Jansma, 2002, Strain partitioning and fault slip rates in the Caribbean from GPS measurements, *Geophy. Res. Lett.*, **29** (18), 1856, doi: 10.1029/2002G1015397.

Jansma, P., A. Lopez, G. Mattioli, C. DeMets, T. Dixon, P. Mann, and E. Calais, 2000, Neotectonics of Puerto Rico and the Virgin Islands, northeastern Caribbean, from GPS geodesy, *Tectonics*, **19**, p. 1021-1037.

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REPORTS IN PREPARATION:

Jansma, P. and G. Mattioli, The rigidity of Puerto Rico and the northern Virgin Islands as inferred from GPS geodesy, to be submitted to *Geophys. Res. Lett.*

ABSTRACTS

Jansma, P., G. Mattioli, A. Lopez, C. DeMets, T. Dixon, P. Mann, and E. Calais, 2000, Neotectonics of Puerto Rico and the Virgin Islands, northeastern Caribbean, from GPS geodesy: implications for seismic hazard, American Geophysical Union Annual Meeting, San Francisco, December 2000, invited, Eos Trans., AGU, 81 (48), F1180.

Calais, E., P. Mann, J. Ruegg, C. DeMets, T. Dixon, P. Jansma, G. Mattioli, R. Bilham, 2000, Crustal deformation in the northeastern Caribbean from GPS measurements, American Geophysical Union Annual Meeting, San Francisco, December 2000, invited, Eos Trans., AGU, 81 (48), F1180.

DATA AVAILABILITY

The campaign and continuous GPS data are being archived locally and backed up to DAT and CD. UPRM/UA raw data are not yet publicly available by ftp, because security issues regarding full public access have not been worked out and dedicated computational resources for such public access are not available at this time. Currently, all UPRM/UA GPS data through October 2001 have been placed in the UNAVCO archive following the standard procedures established by the GPS community. PUR3 and CRO1 data are avaliable on-line through the standard archives.

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FIGURES

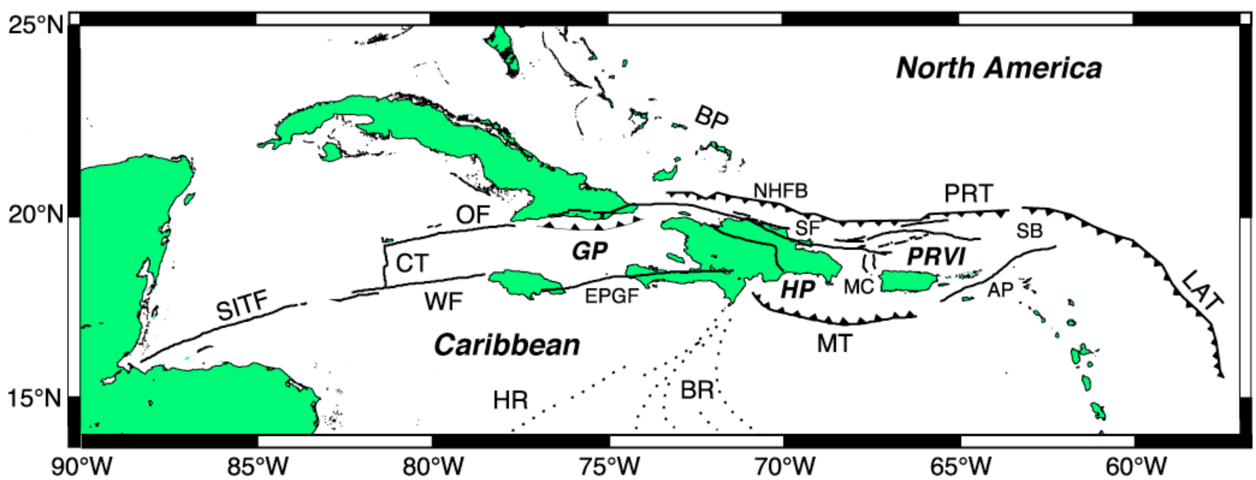

Figure 1: Map of northern Caribbbean plate boundary showing microplates and structures. AP, Anegada Passage. BP, Bahama Platform. BR, Beata Ridge. CT, Cayman trough spreading center. EPGF, Enriquillo-Plantain Garden Fault. GP, Gonave platelet. HP, Hispaniola platelet. HR, Hess Rise. LAT, Lesser Antilles Trench. MR, Mona Rift. MT, Muertos Trough. NHFB, North Hispaniola Fold Belt. OF, Oriente Fault. PRT, Puerto Rico Trench. PRVI, Puerto Rico-Virgin Islands block. SB, Sombrero Basin. SITF, Swan Islands Transform Fault. SPRSF, South Puerto Rico Slope Fault. WF, Walton Fault.

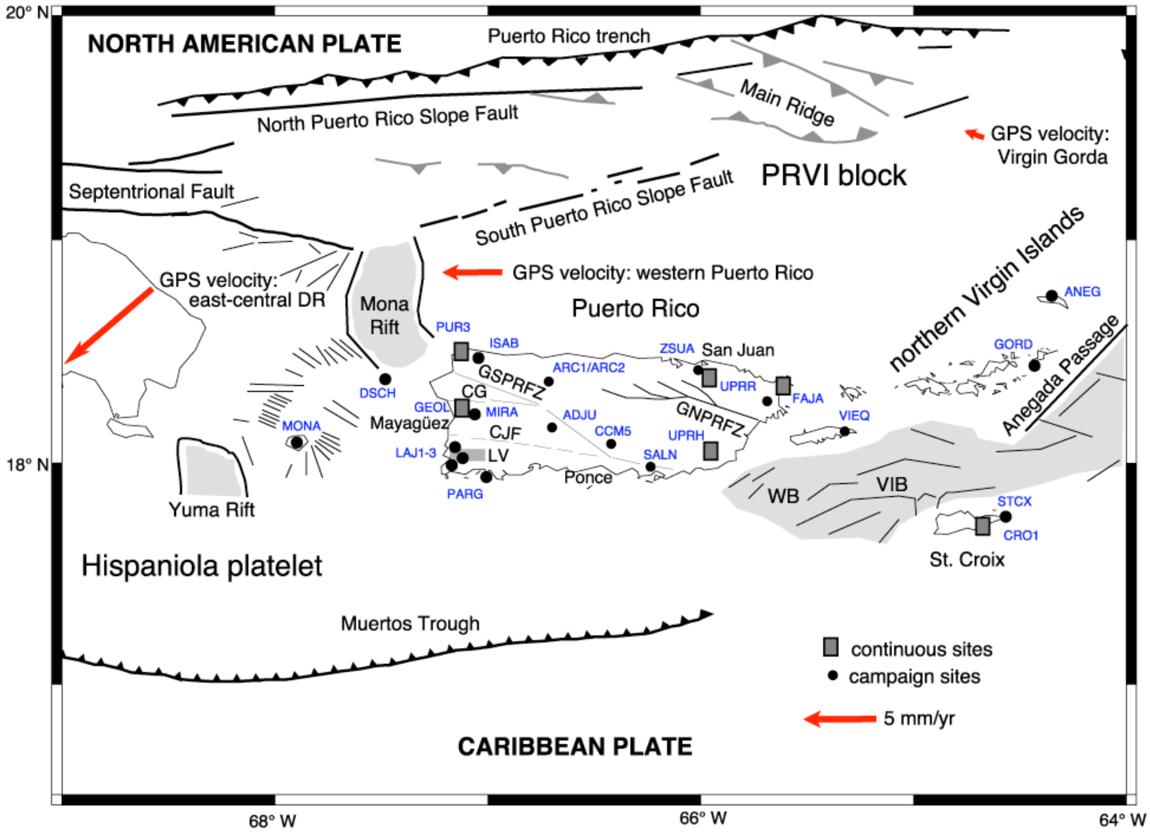

Figure 2. Current mixed-mode GPS geodetic network in the northeastern Caribbbean. GNPRFZ=Great Northern Puerto Rico Fault Zone. GSPRFZ=Great Southern Puerto Rico Fault Zone. CG=Cerro Goden Fault. CJT=postulated Cordillera-Joyuda Faults. LV=Lajas Valley (medium gray shaded recangle in southwestern Puerto Rico). Offshore structures include WB, Whiting Basin; VIB, Virgin Islands Basin. Arrow in Dominican Republic is GPPS-derived velocity for central Hispaniola, south of Septentrional Fault. Arrow north of the island of Puerto Rico is average GPS-derived velocity relative to the Caribbean for sites in western Puerto Rico. Arrow north of the Virgin Islands is GPS=derived velocity relative to Caribbean for site in Virgin Gorda. Length of arrow in lower left corresponds to 5 mm/yr for scale. Error ellipses not shown for clarity.

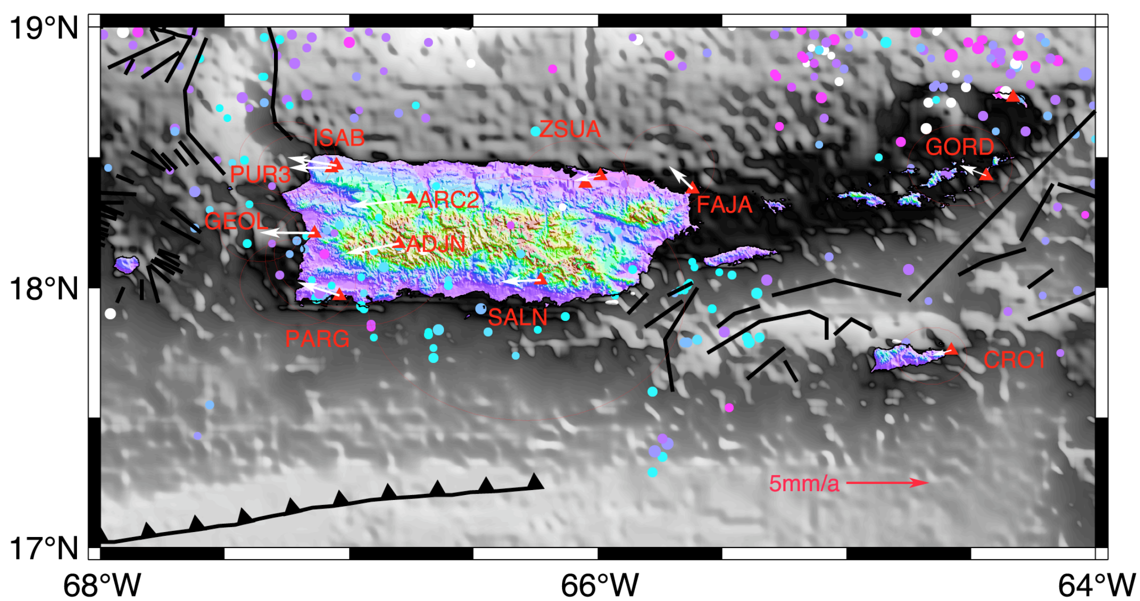

Figure 3. Velocities relative to Caribbean reference frame. Confidence ellipses are 95%. Dots are earthquake epicenters from 1/1/1967 until 2/21/2002 (USGS).